MAGNETICALLY REINFORCED MULTI-STABLE SHELLS FOR BIO-INSPIRED SHAPE ADAPTATION

Andres F. Arrieta[1], Jascha Schmied[2], Hortense Le Ferrand[3], Paolo Ermanni[2], André R. Studart[3]

[1]School of Mechanical Engineering, Purdue University, West Lafayette 47907, IN, USA,
Email: aarrieta@purdue.edu
[2]Laboratory of Composite Materials and Adaptive Structures, ETH Zürich, Zürich 8092, Switzerland
[3]Complex Materials, Department of Materials, ETH Zürich, Zürich 8093, Switzerland

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Abstract
Materials and structures capable of showing large adaptability of properties remain rare in contemporary engineering systems. In most cases so called smart materials featuring multi-physics couplings that rely on nano-scale constitutive properties have been utilized to achieve a degree of adaptability. In contrast, natural material systems are capable of remarkable adaptation by exploiting several effects across different length scales as a result of clever hierarchical architectures. In particular, natural systems are capable of large shape adaptability in response to external stimuli with minimal energy expenditure. In this paper, this bio-inspired approach is utilized to generate fast shape adaptation in composites based on structural multi-stability. A procedure to architecture the micro-structure of a platelet-epoxy composite system utilizing magnetic alignment is followed. The manufacturing process for producing thin multi-stable shells is presented and experimental specimens demonstrating the feasibility of the approach are shown. The herein presented approach departs from the current reliance on specific material properties to produce large shape adaptation. Furthermore, the shape adaptability obtained from hierarchically micro-reinforced composites produces response times orders of magnitude faster than most stimuli responsive materials which depend on slow diffusion driven process.

1. Introduction

Engineering systems capable of dynamic adaptation of otherwise fixed characteristics, e.g. shapes and structural properties, have been recently under intense research focus. Currently, the design of engineering materials and structures heavily relies on the intrinsic attributes of the specific chemistry of the utilised constitutive compounds found in metallic alloys, ceramics, polymers and their combinations [1]. Furthermore when utilizing traditional materials, the possibility for adapting the material and system properties are severely limited after the manufacturing process has concluded. In contrast to this, natural materials and systems show large capabilities for adapting their properties. A new type of dynamically adaptable materials inspired by nature have been introduced in an attempt to depart from the current design paradigm in which static properties are prevalent [2]. An intermediate step into the quest of obtaining dynamically adaptable materials are systems capable of responding to external stimuli to adjust important properties commonly known as shape programmable matter [3] or simply stimuli responsive materials [4]. This class of material systems display striking adaptability exploiting diverse multi-physics couplings from photo-responsive solar panels [5], hygro-elastic swelling [6, 7], magneto-elastic deflection [8], to shape memory due to phase transformations [9]. The implementation of such technologies has

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led to far reaching applications showing the feasibility and potential applications of shape programmable systems. In particular, materials with intrinsically shape adaptable properties can lead to the generation of multiple functionality as illustrated by active foldable systems [3] or diffusive processes [10]. Despite the impressive progress, most examples of shape programmable systems still depend on the specific physical properties of the materials used [11]. Furthermore, the response speed of such systems is still limited by the speed of the control systems of active components or by the very slow time constants associated with diffusive processes.

In contrast to this, nature utilizes hierarchical architectures exploiting physical effects at different length scales to produce remarkable functionality and adaptability using a limited number of constitutive compounds [12, 13]. A powerful approach to implement this design methodology in synthetic materials is to control the spatial distribution of material architectures across different length scales by means of magnetically positioned micro-reinforcement [14]. The method tailors the local mechanical properties by magnetically-controlling the alignment of hard inclusions coated with superparamagnetic nano-particles to realize complex material architectures [15] and remarkable material properties [16]. Indeed, reinforcements mimicking the collagen fibre alignment in wood or pinecones seeds can be designed using this technique to generate self-shaping functionality highlighting the vast design possibilities available when utilizing effects across scales [17]. In this particular case, magnetic responsiveness at the nano-scale is used to control the organization of micro-scale sized reinforcements to generate shape adaptability at the macro-scale.

The authors have recently introduced a novel technique to further expand the possibilities for generating shape change independently of the chemical constitutive compounds based on bio-inspired design principles [18]. In particular, hierarchical architectures are utilized to generate multi-stability in thin shells. Multi-stability is the capacity of a system to exhibit several stable configurations. In structural systems, multi-stability have been utilized at the structural level in a plethora of applications as for generating snapping surfaces [19, 20], morphing structures [21, 22, 23, 24, 25, 26, 27], vibration control [28, 29], mechanical motion amplification mechanisms [30, 31, 32] and energy harvesting devices [33, 34, 35, 36, 37]. Indeed, multi-stability depends only on the geometric properties of the induced pre-strain field (pre-loading) [38], allowing for fast shape adaptation owing to the dynamic instability governing the changes between stable states known as snap-through [39, 40]. Furthermore, very little energy is required to achieve the large deflections entail by changes between stable configurations due the stored strain energy within the structure. Since the stiffness and induced pre-strain locally depend on the arrangement of the micro-reinforcement, the technique for generating complex hierarchical architectures can be utilised to generate material systems exhibiting several statically stable configurations or equilibrium states.

In this paper, the generation of multi-stable systems resulting from a tailored hierarchical micro-structure of bi-layered epoxy plates is further investigated following the seminal work from Schmied et. al. [18] for producing inherent and fast shape adaptability. The design freedom for controlling the alignment of magnetically responsive inclusions to build programmed and complex strain fields induced by thermal stresses occurring during the manufacturing are investigated. This study demonstrates that this concept matches the usual multi-stable structures obtained by fibre reinforced polymers and can be extended for systems having different reinforcement directions. This is illustrated by producing square bi-stable elements showing bending and twisting deformations. This approach can be utilized for producing tessellated multi-stable structures [41] avoiding reinforcement continuity problems, common in fibre reinforced composites. The utilization of hierarchical micro-reinforcement and multi-stability allows for producing material independent shape adaptable structures with response times orders of magnitude faster than diffusion driven process, owing to the snap-through instability governing the changes between stable configurations [31, 42].

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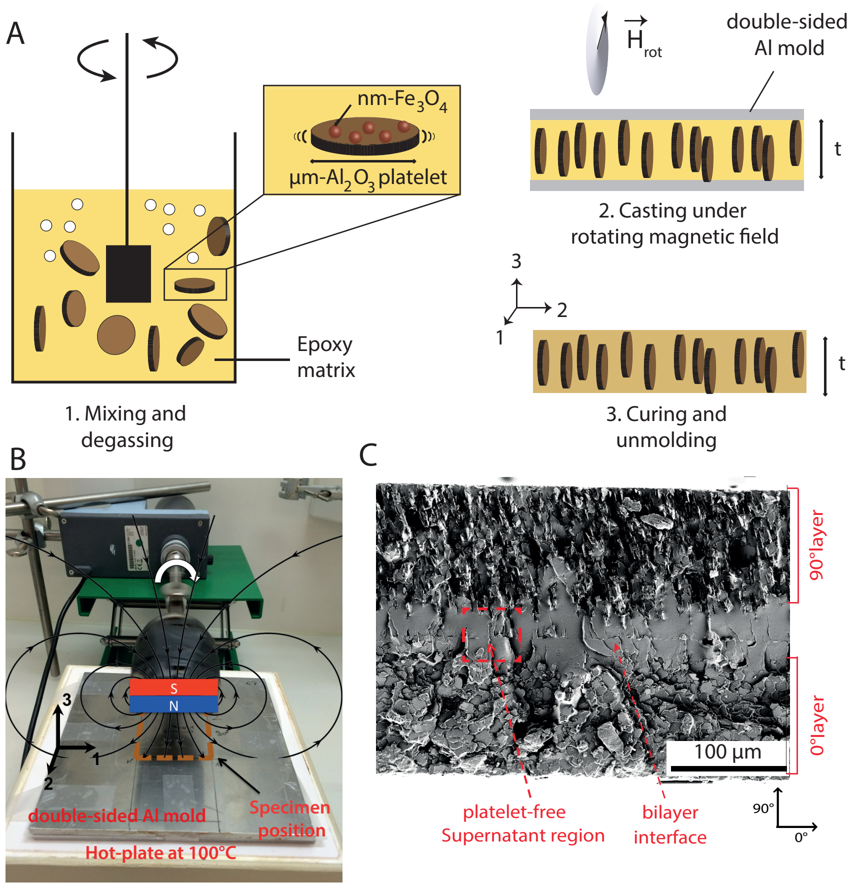

Figure 1. Procedure for the fabrication of anisotropic single layers with controlled thickness using the set-up shown in B). The magnetic field is rotated within the plane parallel to vectors 1 and 3. C) SEM micrograph of a cross-section of a [0°/90°] lay-up bilayer.

2. Manufacturing process: controlling the micro-structure to induce multi-stability

The utilisation of hierarchical material design to produce multi-stable structures requires the production of an asymmetric stiffness distribution and misfit compressive strains about the geometric mid-plane [38]. To achieve this, we utilize the bio-inspired methodology to produce a micro-structure fulfilling the above mentioned requirements. This is achieved by assembling asymmetrically aligned hard inclusions in a liquid epoxy to produce a bilayered micro-structure, as seen in Fig. 1. The known platelet-epoxy systems described in Refs [14, 43] is used throughout this work. In the initial step, micron sized magnetised alumina platelets are mixed with epoxy at the liquid state. A thorough degassing follows after which a drop of the mixture is deposited on an aluminium plate framed by spacers of 300 μm thickness. The solution is then pressed between two aluminium plates, such that the mixture fills the mould with a thickness controlled by spacers as illustrated in Fig. 1.A. A rotating magnetic field is applied during curing at 100°C to align the platelets in the desired plane (1-3 plane in Fig. 1.A). After the curing process is completed, the pre-straining due to differential contraction of the bilayered laminate generates the multi-stable behaviour. In the present investigation a platelet volume fraction of 10 vol% is utilised as it was shown to be the optimum amount of reinforcement for maximizing both the anisotropy in the thermal expansion and in the elastic modulus [18]. The bilayered microstructures of the plates produced exhibit the designed platelet alignment, where one layer contains platelets reinforcing the plane 1-3 while the other layer reinforces the perpendicular plane 2-3 (Fig. 1.C). Such a microstructure is referred in the following text as [0°/90°] lay-up. Additionally, to prevent any loss of bistability from sedimentation, one

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of the layers is turned upside down so that the two platelet-free supernantant regions pile up in the middle of the sample. This manufacturing procedure allows for producing epoxy films reinforced with alumina micro-platelets with tuneable orientation and spatial distributions of reinforcement concentrations.

3. Experimental Results: bio-inspired multi-stable laminates

The manufacturing process explained in section 2 is utilized to produce multi-stable laminates with a designed hierarchical micro-structure. Initially, an orthotropic micro-reinforcement aligned with the perpendicular edges of laminates matching the constant curvatures exhibited by [0°/90°] fibre-reinforced composites [44, 45] are chosen for comparison. Experimental investigations are conducted revealing that a layer thickness, t_i, of 300 μm exhibits multi-stability for an edge thickness of 60 mm, as shown in Fig. 2.A. The shape of the produced micro-reinforced layers can be modificed to produce twisting laminates with an equivalent lay-up of [-45°/45°] are can be seen in Fig. 2.B. Surprisingly, the strain and stresses induced during the curing and cool-down of the films have little sensitivity to the flaws in the specimens, demonstrating the predominance of the stresses built within the material.

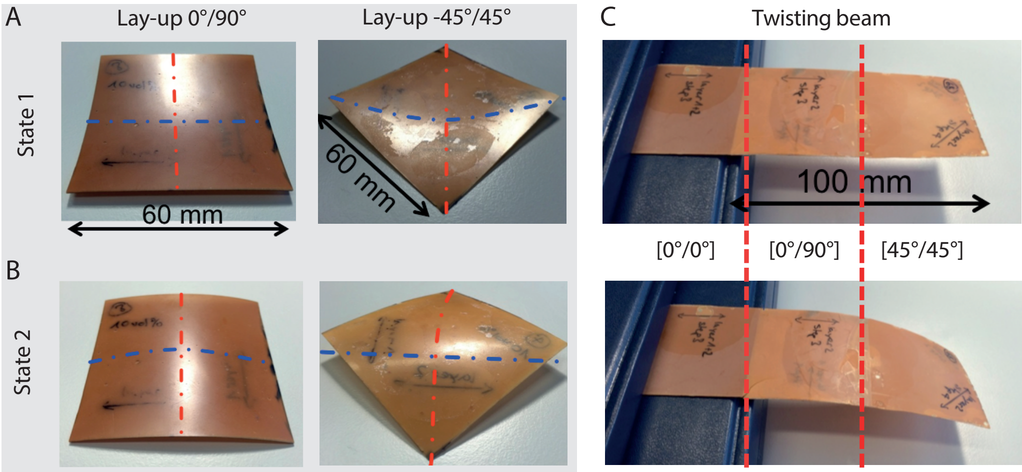

Figure 2. A-B) Platelet-reinforced bi-stable square plates: A) bending and B) twisting specimens with [0°/90°] and [-45°/45°] lay-ups, respectively. C) Juxtaposition of three lay ups featuring different micro-reinforcement architectures: [0°/0°], [0°/90°] and [-45°/45°] producing a bending-twisting multi-stable beam.

We extended these results by combining side by side three different regions with specific micro-reinforcement architectures, namely [0°/0°], [0°/90°] and [-45°/45°], to produce a beam showing 6 stable states enabling deformation modes combining bending and twisting, as can be seen in Fig. 2.C. Extending this procedure to profit from the unique capabilities afforded by the magnetically oriented manufacturing technique herein utilised enables the production of smooth interface zones in which the reinforcement does not show sharp transitions or discontinuities, thus providing a practical alternative to tow steering [46, 47] to produce highly multi-stable laminates [48, 49, 50]. This procedure can be thus utilised to generate material systems with the programmed ability to show different complex shapes capable of dynamic adaptation orders of magnitude faster than state-of-the-art diffusion driven shape programmable materials [17, 10, 51].

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4. Conclusions

The utilisation of bio-inspired hierarchical material architectures have been explored to generate shape adaptable systems with a fast dynamic response based on multi-stable behaviour. The proposed shape adaptability is independent of constitutive material properties and geometrically scalable enabling an adaptation mechanism orders of magnitude faster than present stimuli responsive materials that rely on inherently slow and environment dependent diffusion driven processes. Due to the material independence nature of the structural multi-stability herein utilised, the presented approach can be extended to virtually any combination of composite systems in which the micro-structure can be tailored to achieve the required asymmetric stiffness and pre-strain distributions. The presented methodology allows for producing structures with the ability to exhibit several deformation modes by exploiting combinations of bending and twisting deflections leading to highly multi-stable composites. Furthermore, the ability to locally guide the micro-reinforcement can be used to avoid the problem of interfaces without continuity of reinforcement commonly encountered when spatially varying lay-ups are required in fibre-reinforced composites, extending the validity of the presented results well beyond programmable matter and stimuli responsive systems.

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